INTEGRAL-ISGRI observations of the Cygnus OB2 region

Searching for hard X-ray point sources in a region containing several non-thermal emitting massive stars

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ABSTRACT

Aims. We analyze INTEGRAL-ISGRI data in order to probe the hard X-ray emission (above 20 keV) from point sources in the Cyg OB2 region and to investigate the putative non-thermal high-energy emission from early-type stars (Wolf-Rayet and O-type stars). Among the targets located in the field of view, we focus on the still unidentified EGRET source 3EG J2033+4118 that may be related to massive stars known to produce non-thermal emission in the radio domain, and on the wide colliding-wind binary WR 140.

Methods. Using a large set of data obtained with the IBIS-ISGRI imager onboard INTEGRAL, we run the OSA software package in order to find point sources in the fully coded field of view of the instrument.

Results. Our data do not allow the detection of a lower-energy counterpart of 3EG J2033+4118 nor of any other new point sources in the field of view, and we derive upper limits on the high-energy flux for a few targets: 3EG J2033+4118, WR 140, WR 146 and WR 147. The results are discussed in the context of the multiwavelength investigation of these objects.

Conclusions. The upper limits derived are valuable constraints for models aimed at understanding the acceleration of particles in non-thermal emitting massive stars, and of the still unidentified very-high gamma-ray source TeV J2032+4130.

Key words. stars: early-type – radiation mechanisms: non-thermal – X-rays: stars – gamma rays: observations – acceleration of particles

1. Introduction

With the advent of the Energetic Gamma Ray Experiment Telescope (EGRET) onboard the Compton satellite, our vision of the gamma-ray sky improved significantly. However, among the 271 point sources listed in the third EGRET catalogue (Hartman et al. 1999), most are still unidentified. Many of these high-energy sources can be associated to supernova remnants, active galactic nuclei, pulsars and High-Mass or Low-Mass X-Ray Binaries (respectively HMXRB and LMXRB), but it has also been shown that a few may be coincident with early-type stars (see e.g. Romero et al. 1999). A good example is the EGRET source 3EG J2033+4118 that is located in Cyg OB2, one of the richest OB associations of the Galaxy (Knödlseder 2000).

Cyg OB2 is also interesting in the sense that it harbours 3 O-type stars (Cyg OB2 #5, #8A and #9) known to produce non-thermal radio emission, revealing therefore that these stars are able to accelerate electrons up to relativistic energies. The existence of such a population of relativistic particles opens up the possibility that other non-thermal emission processes are at work in the high-energy domain. For this reason, non-thermal radio emitting early-type stars are considered as candidates for the emission of non-thermal radiation in the hard X-rays and in the γ-rays (see e.g. De Becker 2005). The putative contribution of some of these early-type stars to the γ-ray source 3EG J2033+4118 has already been discussed by Benaglia et al. (2001) and De Becker et al. (2005b). In addition, a few long-period Wolf-Rayet binaries (WR 140, WR 146, and WR 147) located close to Cyg OB2 are also classified as non-thermal radio emitters, and may therefore be non-thermal high-energy sources. In the context of the so-called “standard” model for the non-thermal emission from massive stars, the electrons are accelerated through the Diffusive Shock Acceleration mechanism (DSA, Pittard & Dougherty 2006) by hydrodynamic shocks produced by colliding winds in binary systems. The high-energy emission is expected to arise from the inverse Compton (IC) scattering of UV photons emitted by the stars of the system, even though hadronic processes such as neutral pion decay may also contribute to the γ-rays. However, there are many uncertain parameters in current models which require observations to

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Fig. 1. IBIS-ISGRI mosaic image constructed on the basis of the 715 science windows (FCFOV) between 20 and 60 keV. The point sources detected in the field of view are individually pointed out. The large structures centered on Cyg X-1 are artificial. The coordinate grid specifies the right ascension and the declination.

further constrain the nature of the acceleration process and the efficiency of leptonic and hadronic emission processes. Recent observations with XMM-Newton (between 0.5 and 10.0 keV) of non-thermal radio emitting early-type stars failed to detect unambiguously a non-thermal soft (i.e. below 10 keV) X-ray emission component (Rauw et al. 2002; De Becker et al. 2004a, 2005a, 2006). This non-detection may be explained by the limited availability of UV photons for IC scattering in binary systems characterized by somewhat large separations, and mostly by the fact that the faint putative non-thermal emission may be overwhelmed by the thermal emission from these systems that is much stronger in soft X-rays. For this reason, an investigation of the higher energy domain – where there is no more thermal emission from colliding-winds – is strongly needed.

The existence of the very high-energy $\gamma$-ray source TeV J2032+4130 (Aharonian et al. 2005; Konopelko et al. 2007) in the direction of Cyg OB2 – discovered using Cherenkov telescopes – should also be considered. The nature of this source is still unknown, even though it has been proposed that it may be related to the rich population of massive stars in the Cyg OB2 region (Butt et al. 2003; Torres et al. 2004). The putative relation of TeV J2032+4130 with 3EG J2033+4118 is also worth considering, even though their error boxes are only marginally consistent.

On the basis of a large set of data obtained with the International Gamma-Ray Laboratory (INTEGRAL), De Becker (2005) searched for the presence of high-energy sources related to the massive star population of Cyg OB2, but failed to detect the targets mentioned above. In this paper, we discuss a larger set of INTEGRAL-ISGRI data in order to investigate the hard X-ray emission from the Cyg OB2 region, with the purpose to constrain the flux of the targets mentioned above in the ISGRI bandpass, i.e. between about 20 keV and 1 MeV. The results are also considered in the context of the multiwavelength investigation of the non-thermal emission of radiation from astrophysical sources.

2. Observations and data processing

Time was granted (PI: G. Rauw) to observe the Cyg OB2 region with the IBIS imager (Ubertini et al. 2003) onboard INTEGRAL during revolutions 0080 (Announcement of Opportunity number 1, AO1), and in revolutions 0191, 0210, 0211, 0212, 0213, 0214, 0215, 0216, 0218, 0251, 0252, 0253, 0254 and 0255 (AO2), and these data were analyzed by De Becker (2005). In addition, the same field was observed on the request of many teams, including in the context of the Guaranteed Time.

The data set (observing group) discussed in this paper is constituted of all public science windows (up to revolution 340) where the position of 3EG J2033+4118 appears in the Fully Coded Field of View (FCFOV). We did not consider the Partially Coded Field of View (PCFOV) in order to reduce the impact of noise in our data set, therefore optimizing the efficiency of the source detection procedure. This observing group contains 715 science windows of about 50 min each on average, leading to a total effective observation time of about 2120 ks. We applied the standard ISGRI\(^1\) data analysis procedure using the OSA software (v6.0) provided by the Integral Science Data Center (ISDC, Courvoisier et al. 2003) in order to build a mosaic image and to detect sources. We distributed the events into three energy bands: (1) 20–60 keV, (2) 60–100 keV, and (3) 100–1000 keV. The mosaic image obtained between 20 and 60 keV is shown in Fig. 1.

The detection threshold was fixed at 3$\sigma$. We forced the detection procedure to search only for the sources included in an input catalogue containing a restricted number of potential sources. This approach is useful when dealing with noisy science windows and prevents detection of artificial sources due to ghosts of the bright sources Cyg X-1 and Cyg X-3. The input

\(^1\) As we were interested mainly in a priori rather soft faint sources, we did not consider PICsIT data in our analysis.
Table 1. Input catalogue used for the high-level analysis of the FCFOV around the expected position of 3EG J2033+4118. The sources are sorted by decreasing detection significance level in the first energy band. The last three columns provide the significance of the detection of the sources respectively in the three energy bands selected for the data analysis. In the last three columns, “−” indicates a non-detection. References to previous INTEGRAL observations of most of these sources are given below.

<table>
<thead>
<tr>
<th>Source</th>
<th>Nature</th>
<th>Ref.</th>
<th>α (J2000)</th>
<th>δ (J2000)</th>
<th>Status</th>
<th>σ1</th>
<th>σ2</th>
<th>σ3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyg X-1</td>
<td>HMXRB</td>
<td>2</td>
<td>19h38m 21.7s</td>
<td>+35°12´06”</td>
<td>Detected</td>
<td>4204</td>
<td>1492</td>
<td>480</td>
</tr>
<tr>
<td>Cyg X-3</td>
<td>Microquasar</td>
<td>5</td>
<td>20h32m 26.6s</td>
<td>+40°57´09”</td>
<td>Detected</td>
<td>1252</td>
<td>110</td>
<td>20</td>
</tr>
<tr>
<td>EGO 2030+375</td>
<td>Be/X-ray binary</td>
<td>4,6</td>
<td>20h32m 15.2s</td>
<td>+37°38´15”</td>
<td>Detected</td>
<td>177</td>
<td>21</td>
<td>–</td>
</tr>
<tr>
<td>Cyg X-2</td>
<td>LMXRB</td>
<td>7</td>
<td>21h44m 41.2s</td>
<td>+38°19´18”</td>
<td>Detected</td>
<td>65</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>SAX J2103.5+5454</td>
<td>HMXRB</td>
<td>8</td>
<td>21h03m 33.0s</td>
<td>+45°45´00”</td>
<td>Detected</td>
<td>62</td>
<td>7</td>
<td>–</td>
</tr>
<tr>
<td>KS 1947+300</td>
<td>Be/X-ray binary</td>
<td>9</td>
<td>19h49m 35.6s</td>
<td>+30°12´31”</td>
<td>Detected</td>
<td>47</td>
<td>10</td>
<td>–</td>
</tr>
<tr>
<td>QSO B1957+405</td>
<td>Seyfert 1 galaxy</td>
<td>1</td>
<td>19h59m 28.4s</td>
<td>+40°44´02”</td>
<td>Detected</td>
<td>30</td>
<td>11</td>
<td>–</td>
</tr>
<tr>
<td>IGR J21247+5058</td>
<td>gamma-ray source</td>
<td>10</td>
<td>21h24m 42.0s</td>
<td>+50°59´00”</td>
<td>Detected</td>
<td>22</td>
<td>7</td>
<td>–</td>
</tr>
<tr>
<td>SS Cyg</td>
<td>Dwarf nova</td>
<td>3</td>
<td>21h42m 48.0s</td>
<td>+43°34´36”</td>
<td>Detected</td>
<td>12</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>IGR J2135+5105</td>
<td>gamma-ray source</td>
<td>–</td>
<td>21h33m 50.1s</td>
<td>+51°09´22”</td>
<td>Not detected</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>3EG J2033+4118</td>
<td>gamma-ray source</td>
<td>–</td>
<td>20h33m 36.0s</td>
<td>+41°19´00”</td>
<td>Not detected</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>TeV J2032+4130</td>
<td>gamma-ray source</td>
<td>–</td>
<td>20h32m 07.0s</td>
<td>+41°30´30”</td>
<td>Not detected</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>WR 140</td>
<td>Wolf-Rayet binary</td>
<td>–</td>
<td>20h20m 28.0s</td>
<td>+43°51´16”</td>
<td>Not detected</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>WR 146</td>
<td>Wolf-Rayet binary</td>
<td>–</td>
<td>20h35m 45.1s</td>
<td>+41°22´44”</td>
<td>Not detected</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>WR 147</td>
<td>Wolf-Rayet binary</td>
<td>–</td>
<td>20h36m 43.7s</td>
<td>+40°21´07”</td>
<td>Not detected</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Notes:
1. Bassani et al. (2006); (2) Bazzano et al. (2003); (3) Bird et al. (2004); (4) Camero Arranz et al. (2005); (5) Goldoni et al. (2003); (6) Kuznetsov et al. (2003); (7) Natalucci et al. (2003); (8) Sidoli et al. (2005); (9) Tsygankov & Lutovinov (2005); (10) Walter et al. (2004).

3. Results and discussion

The analysis of our data did not allow us to detect any of the targets that motivated this study. A closer view of the intensity map between 20 and 60 keV – where the expected position of the undetected sources is indicated – is shown in Fig. 2. A summary of the source detection results is given in Table 1, where the significance of the detection is specified for the three energy bands. The main reason for this non-detection could be that we are dealing with a priori faint high-energy sources located in a field populated by several bright sources, among which the very bright High Mass X-Ray Binary Cyg X-1 is dominant. The efficiency of the detection procedure is indeed hampered by the bright source on this image is Cyg X-3. The coordinate grid specifies the right ascension and the declination.

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3.1. 3EG J2033+4118

The upper limits on the count rates obtained in the three energy bands for 3EG J2033+4118 are very consistent across the typical positional error box of IBIS. This suggests that the background is rather homogeneous in this part of the image even though the target position is very close to that of Cyg X-3.
As a second step, we converted these upper limits on the
count rates into fluxes expressed in erg cm$^{-2}$ s$^{-1}$ and in
ph cm$^{-2}$ s$^{-1}$. It is therefore necessary at this stage to make an
assumption on the model of the high-energy emission in the
energy bands used in our ISGRI data analysis. Considering that
the high-energy emission is produced by IC scattering, we may
expect an emission spectrum in the form of a power law with a
photon index equal to 1.5 (this value is expected for IC emission
produced by a population of relativistic electrons accelerated by
the DSA mechanism in the presence of strong shocks, see e.g.
De Becker 2005). We built a synthetic model by folding such a
power law affected by an arbitrary normalization parameter with
the response matrices of ISGRI (response matrix and ancillary
response) using the XSPEC software. We then scaled the normal-
ization parameter of the model in order to match the count rate
of the fake spectrum with the upper limit on the count rate in
the complete ISGRI bandpass. The flux was then estimated on
the basis of this scaled synthetic model in each energy band.
The upper limits on the fluxes are given in Table 2.

As mentioned in the introduction, this unidentified γ-ray
source may be related to the population of O-type stars located
in Cyg OB2. In such a scenario, the high-energy emission may
be explained by the combined IC emission from the three non-
thermal radio emitting stars Cyg OB2 #5, #8A and #9. In or-
der to disentangle the putative high-energy contributions from
these objects, we need to determine accurately their stellar, wind,
and orbital parameters. The best known system is undoubtedly
Cyg OB2 #8A whose orbital solution (De Becker et al. 2004b)
has been further validated by radio and X-ray observations re-
vealing strong phase-locked variations with the same ephem-
erisms (Blomme 2005; De Becker et al. 2006). Cyg OB2 #5 is known
to be a triple system (Contreras et al. 1997) but no orbital solution
exists for the third component. For Cyg OB2 #9, the existence of a
companion has not yet been revealed even though strong varia-
tions of the radio flux are in agreement with a long period binary
scenario (Van Loo 2005). An optical campaign is currently under
way aiming at the investigation of the multiplicity of this latter
target. Provided detailed information are gathered on these ob-
jects, state-of-the-art models (see e.g. Pittard & Dougherty 2006)
may be applied in order to estimate the respective contributions
to the expected non-thermal high-energy emission from these
O-type stars. This constitutes the obvious next step in the study
of the non-thermal phenomena related to these early-type stars.

It should be noted that the power law model generally used to
reproduce the expected non-thermal high-energy emission from
colliding-wind binaries does not necessarily hold in the EGRET
bandpass. On the one hand, the emission process at work above
100 MeV may be different form IC scattering, as it may be due
to a hadronic process such as neutral pion decay. On the other
hand, assuming that the γ-rays detected by EGRET come from
IC emission, the index of the power law at these energies may be
very different from that characterizing the spectrum at a few tens
of keV. The extrapolation to keV energies of the EGRET emis-
sion level measured above 100 MeV is therefore not expected to
carry any relevant physical meaning.

3.2. WR stars

We also estimated the upper limits on the flux following the same
procedure as above in the case of the WR stars included in our
catalogue. The first target worth considering here is the long pe-
riod binary WR 140 (WC7 + O4.5). According to the ephemeris
published by Marchenko et al. (2003), our data sets covers orbital
phases between 0.23 and 0.56, even though most of the science
windows (~65%) have been obtained between phases 0.41 and
0.48. For WR 140, the upper limits are slightly different to those
obtained in 3EG J2033+4118 (see Table 2). We note that these
values are indeed larger than the level of high energy emission
predicted by several colliding-wind binary models developed by
Pittard & Dougherty (2006)$^{6}$ for WR 140. However, the fluxes
predicted by some models used by Pittard & Dougherty (2006)
are larger than the upper limits deduced from the data. In particu-
lar, the predicted flux in the 60–100 keV energy band of model H
of Pittard & Dougherty (2006) is 4.2 × 10$^{-5}$ ph cm$^{-2}$ s$^{-1}$
(5.6 × 10$^{-12}$ erg cm$^{-2}$ s$^{-1}$). The predicted flux for model J of 2.8 ×
10$^{-5}$ ph cm$^{-2}$ s$^{-1}$ is just below the upper limit in the 60–100 keV
band.

In models G-J of Pittard & Dougherty (2006), it is consid-
ered that the Razin effect is the cause of the turndown of the ra-
dio spectrum at GHz frequencies. The fact that these models are
rejected – considering our upper limits – invalidates this latter
scenario, and favors a scenario where the turndown is due to
the free-free absorption by the circumstellar winds (models A-F).
This model selection implies also that the B-field at the apex
of the wind collision region is of order 1 G at the orbital phase
examed (0.837) by Pittard & Dougherty (2006), rather than a
factor of 10 lower (models A-F consider larger magnetic en-
ergy densities than models G-J). To place more stringent con-
straints on the B-field will require actual detection of IC emis-
sion. Unfortunately, the predicted IC fluxes from models A-F
are typically two orders of magnitude below the upper limits
presented here. They are therefore completely out of reach of
INTEGRAL even considering several tens of Ms of observation.

We note that this comparison between predictions and obser-
vations is based on the assumption that the relativistic elec-
tron properties at the time of the radio observation considered by
Pittard & Dougherty (2006) are similar at the orbital phases cov-
ered by the INTEGRAL observations. However, as we are deal-
ing with an eccentric binary, the properties of the colliding-wind
region are expected to vary with the orbital phase. In order to
lift this assumption, simultaneous radio and improved sensitiv-
ity X-ray observations are needed.

We also investigated the case of the two very long pe-
riod colliding-wind binaries WR 146 (WC5 + O8) and WR 147

$^{3}$ We note that the position of WR 140 is coincident with the error box
of the EGRET source 3EG J2022+4317 (Romero et al. 1999; Benaglia
& Romero 2003).

$^{6}$ The approach developed by Pittard & Dougherty (2006) consists in
fitting models to radio data in order to determine the population and spa-
tial distribution of relativistic electrons without an a priori knowledge
of the magnetic field strength.
(WN8h + B0.5V) (see respectively Dougherty et al. 2000 and Williams et al. 1997). Their observational upper limits are the same as for 3EGJ2033+4118, suggesting that the background reaches a rather uniform level in the region of the image where these targets are located. In the case of WR 147, we note that much better radio observations are needed in order to apply correctly a model such as that of Pittard & Dougherty (2006) and make detailed predictions on their non-thermal high-energy emission level to be confronted to our upper limits. Using preliminary fits of radio data for WR 146 and WR 147, we predict high-energy fluxes at least one order of magnitude below the observational upper limits. But it is worth noting that the uncertainty on the power law index of the relativistic electron population derived from the fit of radio data is too large to lead too any firm conclusion. We note also that the non detection of WR 147 is in agreement with the prediction by Reimer et al. (2006) who argued that several Ms of observation with INTEGRAL may be needed to detect it.

We note also that these three WR systems were considered in the study of Benaglia & Romero (2003) of the γ-ray emission from WR binaries. According to their model, IC fluxes of about $8 \times 10^{-4}$, $1 \times 10^{-4}$ and $1 \times 10^{-3}$ ph cm$^{-2}$ s$^{-1}$ are expected respectively for WR 140, WR 146 and WR 147 in the INTEGRAL-IBIS energy range, i.e. between 15 keV and 10 MeV. Using the same power law model, we estimated the photon fluxes in the three energy bands used for our data analysis. We obtain predicted values that are larger than our observational upper limits for WR 140 and WR 147. As a result, our upper limits for WR 140 and WR 147 are inconsistent with the model of Benaglia & Romero (2003).

### 3.3. TeV 2032+4130

According to Konopelko et al. (2007), the angular extent of this target is less than 6 arcmin and it can therefore be considered as a point source (the IBIS point spread function is about 12 arcmin). The upper limits on the flux that we derived for the TeV source are the same as those of 3EGJ2033+4118 in the three energy bands. This is not surprising as the background seems rather homogeneous in the sky region where these two sources – along with WR 146 and WR 147 – are located (see Fig. 2). The improved upper limits on the hard X-ray flux from this unidentified object are expected to constitute helpful constraints for future studies aiming at unveiling the nature of recently discovered very-high energy sources. As the process responsible for the high-energy emission is still a completely open issue, we did not make any hypothesis on the emission model to convert the upper limits into energy or photon fluxes. We note that the recent analysis by Butt et al. (2006) of public ISGRI data (including PCFOV data, in addition to the FCFOV data set used in this study) below 300 keV did not lead to a detection of TeV 2032+4130 neither.

### 3.4. Other sources

As mentioned in Table 1, several point sources have been detected with our data. It is not the purpose of this paper to go through the details for these sources. Most of them are rather bright sources that have been discussed in several papers (see references in Table 1), except for the dwarf nova SS Cyg. This target is interesting in the sense that not so many dwarf novae have been detected in hard X-rays. The detection of this cataclysmic variable with INTEGRAL has already been reported in the soft ISGRI bandpass with a detection significance of $7\sigma$ and a count rate of $0.71 \pm 0.10$ cts s$^{-1}$ between 20 and 40 keV (Bird et al. 2004), but SS Cyg was not detected at higher energies. The count rate we report here between 20 and 60 keV is $0.77 \pm 0.06$ cts s$^{-1}$ with a detection significance of $12\sigma$. The 3-$\sigma$ upper limits we derived in the 60–100 keV and 100–1000 keV energy bands are respectively 0.11 and 0.14 cts s$^{-1}$. In order to compare the count rates obtained by Bird et al. (2004), we ran the OSA software in narrower energy bands, i.e. 20–40 and 40–60 keV, and we derived a count rate of $0.69 \pm 0.05$ cts s$^{-1}$ in the former band, with a detection significance of $3\sigma$. SS Cyg is still not detected at the 3$\sigma$ level above 40 keV.

### 4. Conclusions

Our investigation of the high energy emission in the ISGRI bandpass did not lead to the detection of point sources related to non-thermal radio emitting massive stars in the Cyg OB2 region. We however derived upper limits on the count rate of these sources in three energy bands in order to constrain the high energy emission level of these targets.

These upper limits provide significant constraints on modelling efforts related to the non-thermal emission processes likely to be at work in massive star environments. Several model fits to the synchrotron radio emission from WR140 yield IC fluxes which are inconsistent with the INTEGRAL upper limits presented here, although the use of isotropic formulae for the IC emission means that there is some uncertainty attached to these predictions (see Reimer et al. 2006; Pittard & Dougherty 2006). A key theme of the Pittard & Dougherty (2006) models which remain viable is that the non-thermal electron energy spectrum is flatter than the canonical value expected from DSA. It is possible that such a spectrum may be achieved by the further acceleration of particles within a highly turbulent wind-wind collision region, as arises when the stellar winds are structured (Pittard 2007). The spectral slope of any future detected IC emission will allow much tighter constraints to be placed on the underlying population of relativistic particles in these systems and the physical mechanisms behind their acceleration. The advent of future high-energy observatories such as GLAST in γ-rays, and NeXT or SYMBOL-X in the hard X-ray domain, is expected to open up new prospects in this context.

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